

Smith's Cloud: a High-velocity Cloud Colliding with the Milky Way

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ABSTRACT

New 21cm HI observations made with the Green Bank Telescope show that the high-velocity cloud known as Smith’s Cloud has a striking cometary appearance and many indications of interaction with the Galactic ISM. The velocities of interaction give a kinematic distance of 12.4 ± 1.3 kpc, consistent with the distance derived from other methods. The Cloud is $> 3 \times 1$ kpc in size and its tip at $(\ell, b) \approx 39^\circ - 13^\circ$ is 7.6 kpc from the Galactic center and 2.9 kpc below the Galactic plane. It has $> 10^6 M_\odot$ in HI. Its leading section has a total space velocity near 300 km s^{-1} , is moving toward the Galactic plane with a velocity of $73 \pm 26 \text{ km s}^{-1}$, and is shedding material to the Galaxy. In the absence of drag the Cloud will cross the plane in about 27 Myr. Smith’s Cloud may be an example of the accretion of gas by the Milky Way needed to explain certain persistent anomalies in Galactic chemical evolution.

Subject headings: Galaxy: halo – Galaxy: evolution – ISM: Clouds — ISM: individual (Smith’s Cloud)

1. Introduction

High-velocity Clouds (HVCs) cover as much as 40% of the sky and have been hypothesized to be the remnants of the formation of the Milky Way, products of a Galactic fountain, material stripped from the Magellanic Clouds, satellites of the Milky Way, and objects in the Local Group (Wakker & van Woerden 1997; Blitz et al. 1999; Braun & Burton 1999; Lockman et al. 2002; Maller & Bullock 2004; Connors et al. 2006). Several have distance determinations which place them in the halo of the Galaxy with $M_{\text{HI}} \sim 10^6 - 10^7 M_{\odot}$ (Thom et al. 2007; Wakker et al. 2007, 2008). Some have a cometary morphology and kinematics suggesting that they are interacting with an external medium (Mirabel & Morras 1990; Brüns et al. 2000; Brüns & Mebold 2004; Peek et al. 2007).

Smith’s Cloud (Smith 1963) is a large, coherent HI feature also called the Galactic Center Positive (GCP) complex (Wakker & van Woerden 1997). Its velocity of $+100 \text{ km s}^{-1}$ is only slightly larger than permitted by Galactic rotation at its location ($\ell, b \approx 39^\circ, -13^\circ$), and Smith concluded that it was most likely part of the Milky Way disk. In recent years, however, it has been classified as a high-velocity cloud because it lies far beyond the main HI layer (Lockman 1984; Wakker & van Woerden 1997). It has been interpreted variously as a cloud expelled from the disk (Sofue et al. 2004), or the gaseous component of the Sgr dwarf spheroidal galaxy (Bland-Hawthorn et al. 1998). We have made an extensive survey of Smith’s Cloud in the 21cm HI line using the Green Bank Telescope, whose angular resolution and sensitivity promised new insights into this system. In particular, we hoped that because of its large angular size we might be able to measure its transverse velocity (e.g., Brüns et al. (2001); Lockman (2003)). A complete discussion of the observations will appear elsewhere. Here we present the initial results on the Cloud’s physical properties and motion.

2. Observations and Data Reduction

Smith’s Cloud was observed in the 21cm HI line using the Robert C. Byrd Green Bank Telescope (GBT) of the NRAO. Spectra were measured in both linear polarizations over a velocity range of 500 km s^{-1} centered at $+50 \text{ km s}^{-1}$ LSR with a channel spacing of 1.03 km s^{-1} and an effective velocity resolution of 1.25 km s^{-1} . Spectra were acquired by in-band frequency-switching while moving the telescope in Galactic latitude or longitude, sampling every $3'$ in both coordinates. In all, more than 40,000 positions were measured over an area of ~ 140 square-degrees. Spectra were edited, calibrated, a third-order polynomial was fit to the emission-free channels, and the data were gridded into a cube with $3/5$ cell spacing. The rms noise in the final data cube is typically 90 mK of brightness temperature in a 1 km s^{-1} channel. The on-the-fly mapping and gridding degraded the angular resolution somewhat from the intrinsic $9/1$ resolution of the telescope to an effective resolution of $10'$ to $11'$.

3. Smith’s Cloud

Figure 1 shows the GBT HI image of Smith’s Cloud at $V_{\text{LSR}} = 100 \text{ km s}^{-1}$. The Cloud has a cometary morphology with a bright compact “tip” and a more diffuse “tail”. Its appearance suggests that it is moving toward the Galactic plane at a 45° angle and is interacting with the Galactic ISM. Direct evidence of this interaction is given in Figure 2, which shows the HI emission in velocity-position coordinates along a cut through the minor axis of the Cloud. The center of the Cloud has a velocity near $+100 \text{ km s}^{-1}$, well-separated from the Galactic HI, but at its edges the lines are broadened and shifted toward the velocity of the Galactic ISM at $\lesssim +35 \text{ km s}^{-1}$. We interpret this as ram-pressure stripping of the Cloud edges. The Cloud’s interaction with the Galactic ISM is shown further in Figure 3, a position-velocity slice along the major axis of the Cloud following a track marked

by the arrows to the upper right and lower left in Fig. 1. There are kinematic bridges between the Cloud and Galactic emission (several marked with dashed arrows) as well as clumps of HI (two marked by solid arrows) at velocities $\lesssim 40 \text{ km s}^{-1}$ which correspond to gaps in the Cloud. The clumps are likely material stripped from the Cloud.

4. Distance to the Cloud

Portions of Smith’s Cloud appear to have been decelerated by the ambient medium through which it moves, and we use this to estimate a distance to the Cloud. The GBT data show disturbances in Galactic HI attributable to the influence of Smith’s Cloud at $V_{\text{LSR}} \geq 35 \text{ km s}^{-1}$ but not at $V_{\text{LSR}} \leq 0 \text{ km s}^{-1}$. If Smith’s Cloud is interacting with Galactic gas whose normal rotational velocity is in this range, it implies that the Cloud has a distance $11.1 < d_k < 13.7 \text{ kpc}$; the “far” kinematic distance for a flat rotation curve with $R_0 = 8.5 \text{ kpc}$ and $V_0 = 220 \text{ km s}^{-1}$.

There are other determinations of the distance. The brightness of diffuse H_α emission from the Cloud and a model for the Galactic UV flux give either 1 or 13 kpc (Bland-Hawthorn et al. 1998; Putman et al. 2003). Recently Wakker et al. (2008) have bracked the distance by looking for the Cloud in absorption against several stars, finding $10.5 < d \leq 14.5 \text{ kpc}$. The three methods give identical results, and we adopt the kinematic distance $d = 12.4 \pm 1.3 \text{ kpc}$ for the remainder of this Letter.

5. Properties of the Cloud

Smith’s Cloud lies in the inner Galaxy below the Perseus spiral arm, $R = 7.6 \text{ kpc}$ from the Galactic center. Properties of the Cloud from the GBT data are presented in Table 1. The brightest HI emission at $\ell, b = 38^\circ 67' - 13^\circ 41'$ is near the Cloud tip. The HI mass of 10^6

M_{\odot} is a lower limit because the Cloud appears to consist of multiple fragments spread over a wide area, not all of which are covered in the GBT map. It probably contains a significant mass in H^+ as well (Wakker et al. 2008). The HI line width Δv (FWHM) varies from ≤ 10 km s $^{-1}$ in a band from the Cloud tip down along the major axis, to > 20 km s $^{-1}$ in the Cloud’s tail and at its edge, where the sight-line through the Cloud intersects regions with a great spread of velocity (e.g., Figs. 2 and 3). The Cloud as a whole is not self-gravitating, and even the most compact components have only 1% of their virial mass.

There are narrow unresolved ridges of intermediate-velocity HI with $N_{\text{HI}} = 2 \times 10^{20}$ cm $^{-2}$ at the edge of the Cloud (Figure 4, also marked with the arrow in Fig. 2). There is some cool gas in the ridge, especially toward the tip of the Cloud, but in general the lines from the ridge are broad with $\Delta v = 10 - 20$ km s $^{-1}$. The ridge contains orders of magnitude more gas than would be expected for material swept-up by the passage of the Cloud through the Galactic halo at a distance of a few kpc from the plane (Dickey & Lockman 1990; Howk et al. 2003) but it has an N_{HI} comparable to that of the Cloud. The ridge is most likely material which has been ram-pressure stripped from the Cloud.

In the GBT data the edge of Smith’s Cloud is unresolved along the region of interaction implying a size < 35 pc. The ridge and the edge of Smith’s Cloud do not overlap on the sky, and both have unresolved edges where they are closest, suggesting that we are viewing the interaction at a very favorable angle. The decelerated clumps marked in Fig. 3 have $N_{\text{HI}} = 1 - 2 \times 10^{19}$ cm $^{-2}$ and HI masses of 200 – 400 M_{\odot} . The lower-velocity clump is unresolved with a size < 35 pc, while the higher-velocity clump is elongated with a size $< 35 \times 130$ pc. The linewidths are narrow, 4 and 5.4 km s $^{-1}$, respectively, indicating that the clumps contain gas no hotter than 350 K.

6. Trajectory

Smith’s Cloud covers a large area on the sky and we can hope to derive its complete space motion from its morphology and the systematic change in $V_{\text{LSR}}(\ell, b)$ with position if local effects like drag are small. For a system centered on the Galactic center,

$$V_{\text{LSR}} = \left[R_0 \sin(\ell) \left\{ \frac{V_\theta}{R} - \frac{V_0}{R_0} \right\} - V_R \cos(\ell + \theta) \right] \cos(b) + V_z \sin(b) \quad (1)$$

where V_θ , V_R and V_z are velocity components in the direction of Galactic rotation, outward, and vertically toward the north Galactic pole. The angle θ is measured from the Sun-center line in the direction of Galactic rotation. With Smith’s Cloud we have the exceptional circumstance that all distances and angles are known, so with measurements of $V_{\text{LSR}}(\ell, b)$ and the angle of Cloud motion (assumed to be along its major axis), we can solve for the individual velocity components and calculate the total space velocity $V_{\text{tot}} \equiv \{V_\theta^2 + V_R^2 + V_z^2\}^{\frac{1}{2}}$.

The HI profiles from Smith’s Cloud have complex shapes and a full discussion of the Cloud kinematics is beyond the scope of this Letter. As an initial step we have taken the velocity of the brightest HI in each pixel, averaged this over square-degree regions along the major axis of the Cloud from $(\ell, b) = 36^\circ\text{--}11^\circ$ to $48^\circ\text{--}23^\circ$, and solved for the velocity components. The results are drawn on Fig. 3. The main Cloud has two kinematic groups, each of which shows the regular velocity pattern expected from projection effects of the motion of a coherent object. Table 2 summarizes the results, where the quantity V_{ISM} is the velocity of the Cloud with respect to a corotating ISM at its location, and the uncertainties reflect both the scatter in the data and in the $45^\circ \pm 10^\circ$ assumed angle of motion of the Cloud across the sky. With $V_{\text{tot}} \approx 300 \text{ km s}^{-1}$ the Cloud is bound to the Galaxy. Its motion is prograde, somewhat faster than Galactic rotation, with an outward radial velocity $V_R \sim 100 \text{ km s}^{-1}$. The compact Cloud tip is moving toward the plane with a velocity $V_z = 73 \pm 26 \text{ km s}^{-1}$, while the more diffuse trailing structure appears to have a much lower

vertical velocity of $8 \pm 11 \text{ km s}^{-1}$.

From its current position and velocity we calculate the Cloud’s orbit in the potential of Wolfire et al. (1995). Assuming that drag is not significant, it will cross the Galactic plane at a distance $R \approx 11 \text{ kpc}$ from the Galactic center in about 27 Myr. Retracing its orbit into the past (again neglecting drag), the Cloud reached perigalacticon at $R = 6.9 \text{ kpc}$ some 12 Myr ago, was never more than 3.6 kpc below the Galactic plane, and actually passed through the plane, from above to below, at $R = 13 \text{ kpc}$ about 70 Myr ago. The current orbit is tilted only $\approx 30^\circ$ to the Galactic pole, so we probably view the Cloud at a large angle to the plane of the sky, with its tail closer to us than its tip. These results will likely be modified as we understand the Cloud’s structure in more detail, but the conclusion that large portions of Smith’s Cloud move coherently seems secure.

7. Discussion

All the data on Smith’s Cloud are consistent with the model of a $10^6 M_\odot$ HI Cloud the size of a dwarf galaxy on track to intersect the Galactic plane. We know more about this particular HVC than any other. Its total space velocity of $\approx 300 \text{ km s}^{-1}$ implies that it is bound to the Galaxy and components which are not greatly slowed by drag from the Galactic halo should reach the plane in 27 Myr at a location about 11 kpc from the Galactic center. Its trajectory is rather flat and mostly prograde, and it may have passed through the Galactic plane once before some 70 Myr ago. The Cloud now consists of two coherent kinematic components, as well as material decelerated to much lower velocity.

Studies of Galactic chemical evolution have uniformly concluded that the Milky Way is not a “closed box” but must accrete low-metallicity gas, possibly supplied by HVCs (e.g., Friel et al. (2002); Matteucci (2004); Romano et al. (2006); Putman (2006)). The collision

of an HVC with the disk has also been invoked to explain the largest HI supershells as well as Gould’s Belt (Tenorio-Tagle et al. 1987; Mirabel & Morras 1990; Comeron & Torra 1994). While there are HVCs that show evidence of interaction with the Milky Way halo (Brüns & Mebold 2004) there are only a few known to be interacting with the Galactic disk (Lockman 2003; McClure-Griffiths et al. 2008) and these are located in the outer parts of the Galaxy, far from the main star-forming regions. Smith’s Cloud is exceptional in that it is entering the Milky Way at $R \lesssim R_0$.

At its current distance of ~ 3 kpc from the Galactic plane the Cloud is probably encountering a mix of warm H^+ and 10^6 K gas with a total density in the range 10^{-3} to 10^{-4} cm^{-3} , though Galactic HI clouds at this height are not out of the question (Lockman 2002; Howk et al. 2003; Benjamin 2004; Pidopryhora et al. 2007). We find several Smith Cloud clumps with $M_{\text{HI}} \approx 100 M_\odot$ which have been decelerated by $> 50 \text{ km s}^{-1}$ suggesting that the ambient ISM is irregular with large density variations. The nature of the Cloud’s interaction with the ISM will depend on its internal properties which are not yet known, but Smith’s Cloud shows every evidence of being disrupted and may not survive much longer as a coherent structure.

Does this cloud have a galactic or extragalactic origin? Is Smith’s Cloud a true high-velocity cloud? Its HI mass is in the range of HVCs like Complex C, Complex H, and the Cohen Stream (Lockman 2003; Wakker et al. 2007, 2008), and given its estimated orbit, it is hard to envision an event that would accelerate more than $10^6 M_\odot$ of material to such a high space velocity with a significant radial component. However, an extragalactic origin is somewhat problematic as well. If it were extragalactic, it is puzzling that the orbit is tilted by only 30° from the Galactic plane, is prograde, and differs from the ambient ISM by only 130 km s^{-1} . Kinematically, then, it might appear to be more of an intermediate- than a high-velocity cloud, but presumably its orbit must have been affected by drag well

before the current epoch (Benjamin & Danly 1997). Its internal kinematics suggest that it has already fragmented (Fig. 3). A key observational datum is the Cloud’s metal abundance to establish exactly what kind of gas it is depositing in the Galaxy. For this Letter we have analyzed only a fraction of the information in the GBT HI spectra. A more detailed analysis of the GBT data and additional measurements of this extraordinary and beautiful object are underway.

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Facilities: GBT

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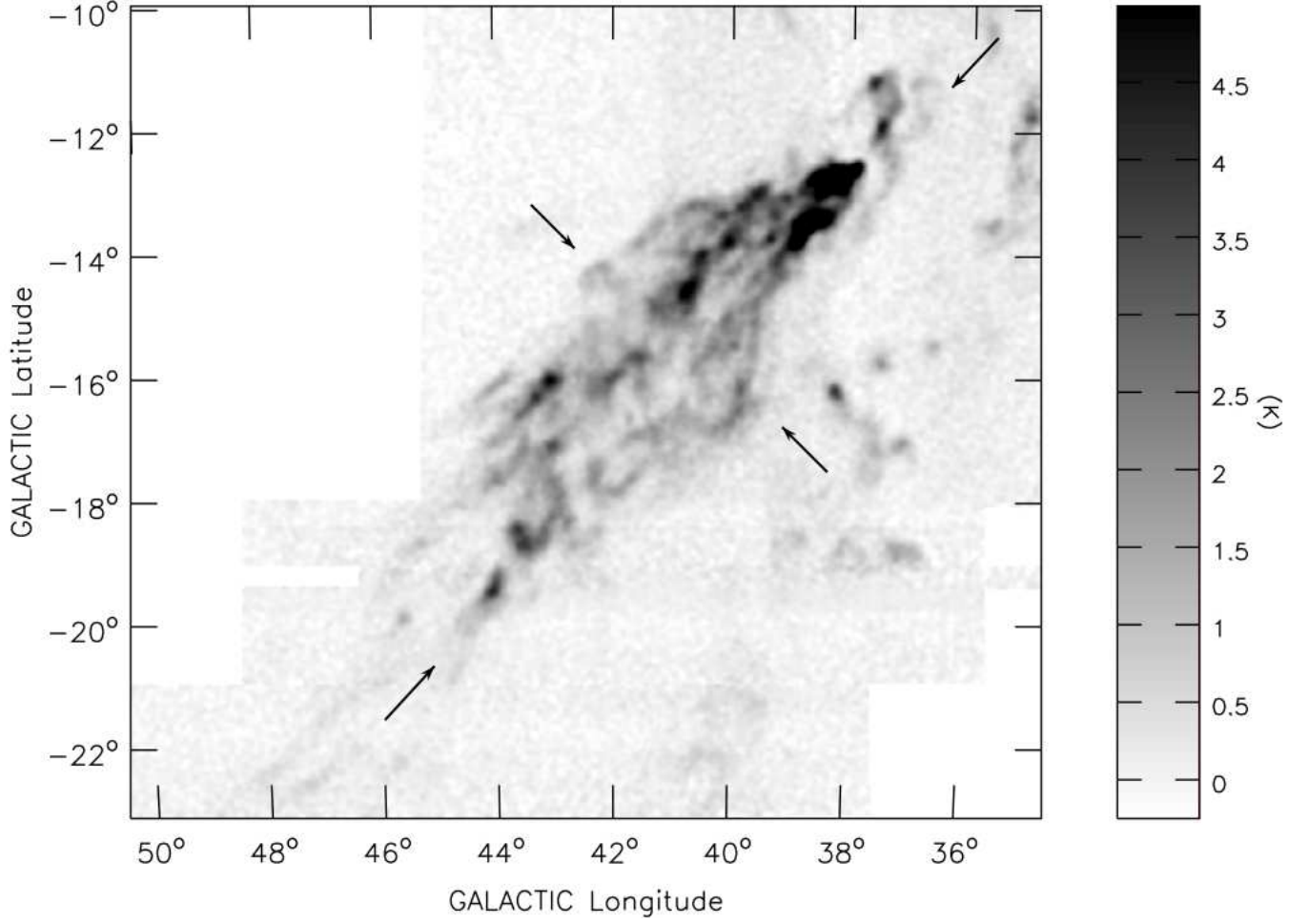


Fig. 1.— GBT HI image of Smith’s Cloud at $V_{\text{LSR}} = 100 \text{ km s}^{-1}$ showing the cometary morphology strongly suggesting that the Cloud is moving to lower longitude and towards the plane, and is interacting with the Galactic ISM. Arrows mark the tracks of the velocity-position slices of Figs. 2 and 3.

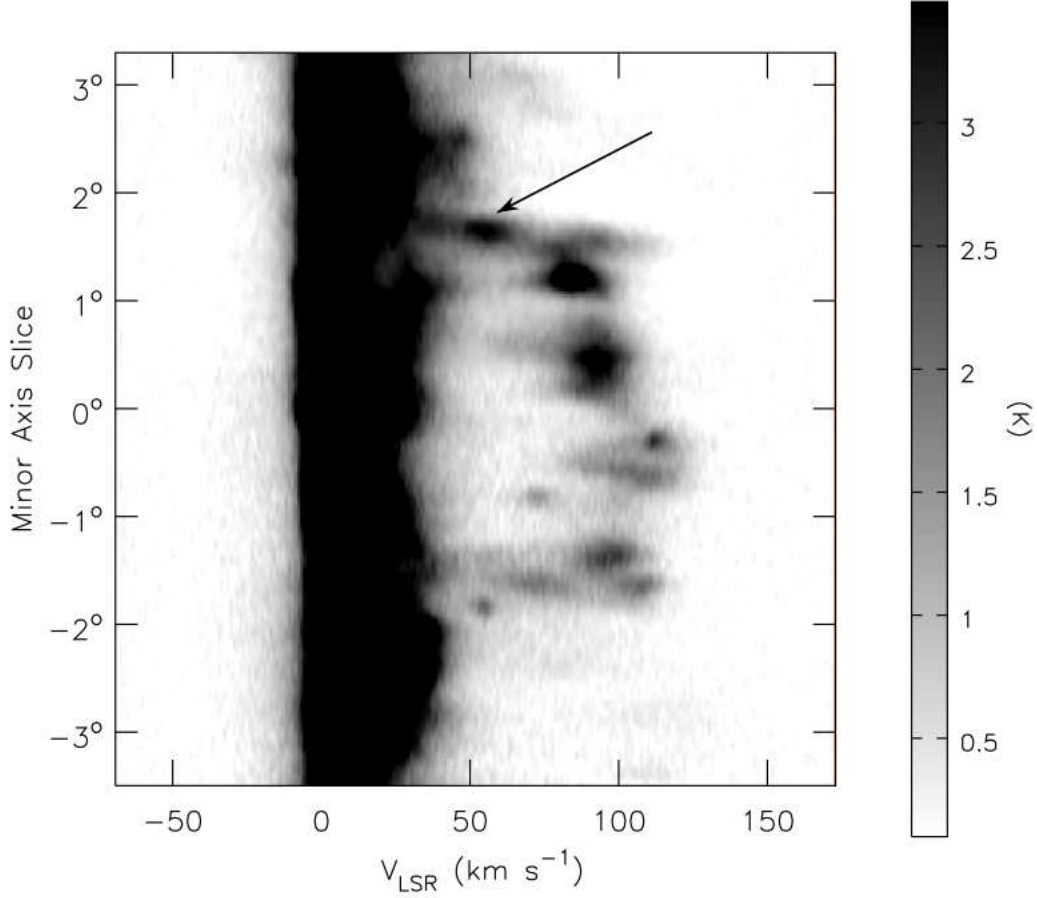


Fig. 2.— GBT HI velocity-position slice through Smith’s Cloud along a track through the minor axis of the Cloud (marked by arrows in Fig. 1). The edges of the Cloud show a sharp gradient in velocity from $V_{\text{LSR}} \sim 100 \text{ km s}^{-1}$ to the lower velocities of Galactic HI. We interpret this as evidence of the interaction between the Cloud and the gaseous halo of the Milky Way. The arrow marks the decelerated ridge shown in Fig. 4.

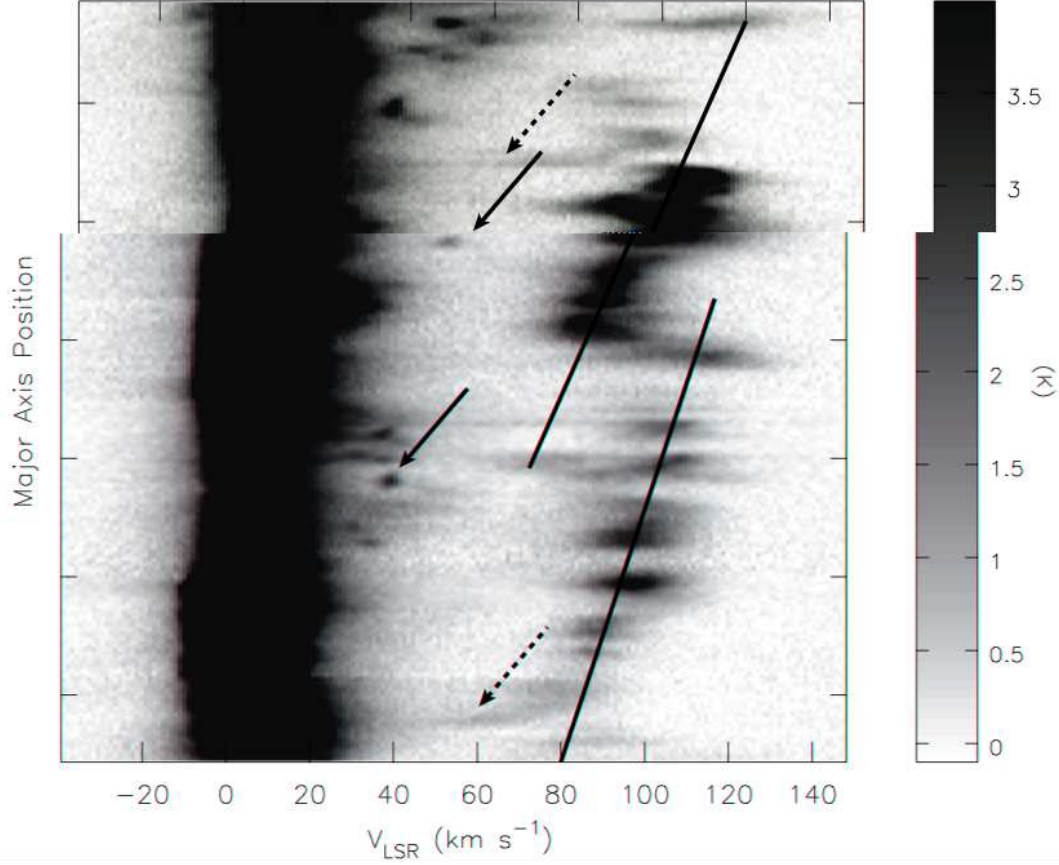


Fig. 3.— GBT HI velocity-position slice through the major axis of the Cloud at the location of the arrows in Fig. 1. Marks on the vertical axis are every 157.5. Along this track there are HI clumps at low velocity matching gaps in the main Cloud. The clumps have likely been stripped from the Cloud. Two are marked by solid arrows. Two line wings which form kinematic bridges between the Cloud and Galactic gas are marked with dashed arrows. The main part of the Cloud shows systematic velocity gradients from the changing projection of its space velocity with respect to the LSR. The tilted lines show the expected run of V_{LSR} with position for $V_{\text{tot}} = 296 \text{ km s}^{-1}$ (upper part of the Cloud) and $V_{\text{tot}} = 271 \text{ km s}^{-1}$ (lower part). The Cloud consists of at least two coherent kinematic pieces.

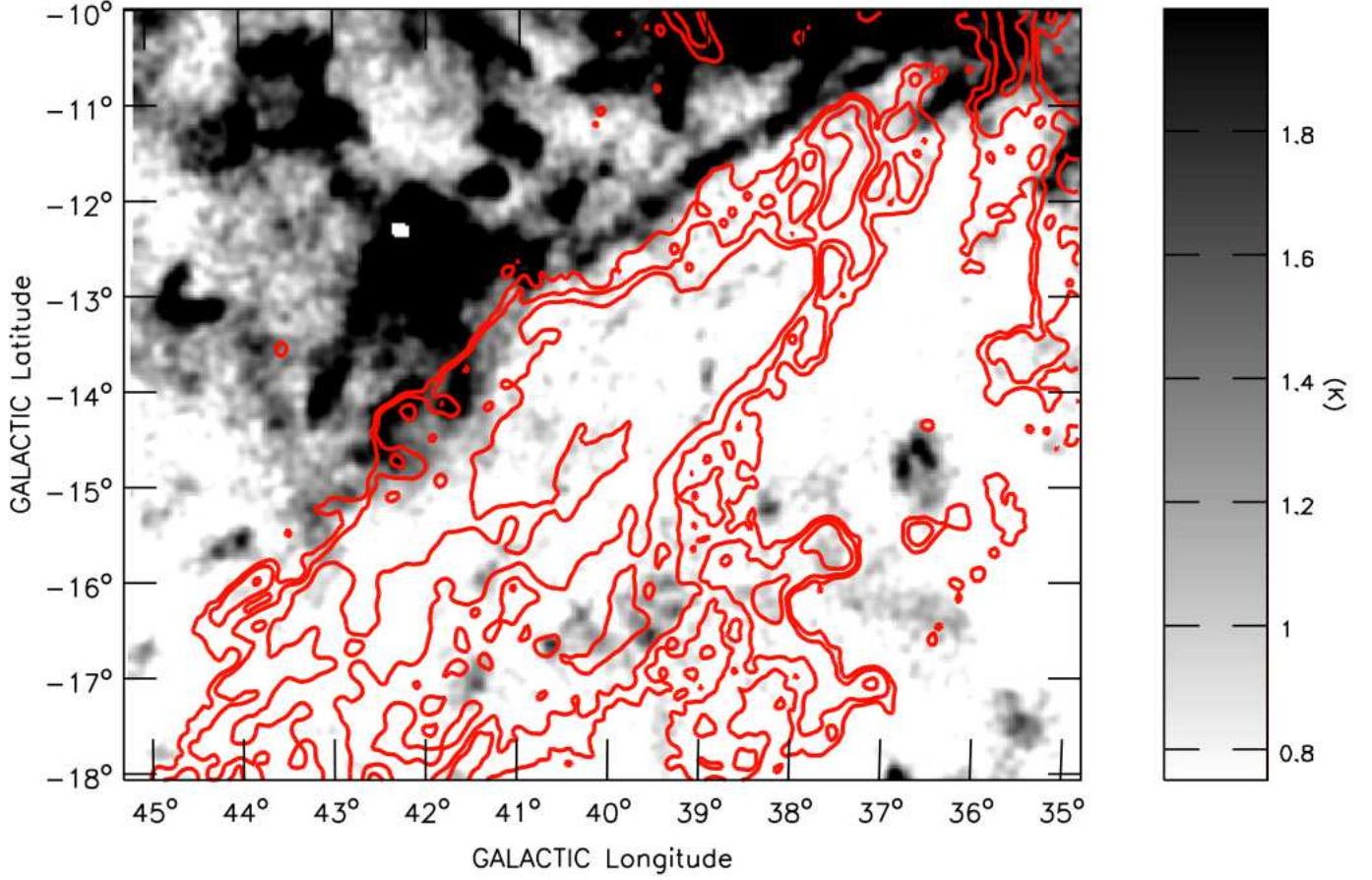


Fig. 4.— HI in a 1 km s^{-1} wide channel at 51 km s^{-1} (gray scale) with superimposed contours of Smith’s Cloud showing the ridge of gas resulting from the encounter of the Cloud with the Galactic halo. We believe that the lower velocity ridge is material stripped from the Cloud. The Cloud emission is integrated over 90 to 145 km s^{-1} and contours are drawn at 7 , 14 and 35 K km s^{-1} .

Table 1. HI Properties of Smith’s Cloud

Property	Value
(1)	(2)
ℓ, b	$38^{\circ}67 - 13^{\circ}41$
Distance (kpc)	12.4 ± 1.3
R (kpc)	7.6 ± 0.9
z (kpc)	-2.9 ± 0.3
T_b (K)	15.5
Δv (km s $^{-1}$)	16.0
N_{HI} (cm $^{-2}$)	5.2×10^{20}
V_{LSR} (km s $^{-1}$)	99 ± 1
HI Mass (M_{\odot})	$> 10^6$
Projected Size (kpc)	3×1

Note. — All but integral quantities apply to the direction of greatest N_{HI} at the position $\ell, b = 38^{\circ}67\text{-}13^{\circ}41$.

Table 2. Kinematics of Smith’s Cloud

Location	V_R	V_θ	V_z	V_{tot}	V_{ISM}
	(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)	(km s ⁻¹)
(1)	(2)	(3)	(4)	(5)	(6)
Tip	94 ± 18	270 ± 21	73 ± 26	296 ± 20	130 ± 14
Tail	129 ± 6	220 ± 11	8 ± 11	271 ± 6	130 ± 5

Note. — V_R is the velocity outward from the Galactic Center and V_{ISM} is the total velocity of the Cloud with respect to the corotating Galactic ISM at its location.